REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)***	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
28-10-2010	Final Report	01-Oct-07 - 01-Oct-10

4. TITLE AND SUBTITLE

Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge

5a. CONTRACT NUMBER
ISTC Registration No: 3794

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Dr. Anatoly Ivanovich Klimov

5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Institute for High Temperature - RAS (IVTAN)
Izhorskaya str., 13/19
Moscow 127412
Russia

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
Unit 4515 BOX 14
APO AE 09421

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
ISTC 07-7008

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report results from a contract tasking Institute for High Temperature - RAS (IVTAN) as follows: We plan to use high voltage capacity HF plasma generator (TeslaÆs coil HF plasma generator) to create longitudinal plasmoid in high-speed vortex gas flow (Vf~ 100m/s and higher) and study of plasmaoidÆs physical properties of in this Project. There is simple tuning of longitudinal plasmoid parameters by power feedback between capacity HF power supply and this plasmoid (tuning of resonance regime). There are optimal conditions for obtaining longitudinal plasma vortex by combined discharge plasma generator: high voltage pulse repetitive generator (ionizer) and continuous high current HF generator simultaneously. These conditions are absent in arc discharge of a traditional plasmatron. So, capacity HF plasma generator is optimal one for stable longitudinal plasmoid creation in high-speed vortex gas flow. Remember that we are succeeded in generation of a longitudinal HF plasmoid (up to 2 m) in high-speed vortex airflow at M~0.8 and static pressure about Pst~1 Bar namely. Stimulated vibration-translation V-T relaxation and electronic exited energy level-translation relaxation are possible in a longitudinal non-equilibrium plasmoid. The main goal of this Proposal is a study of plasma-chemical kinetics and stimulated relaxation processes in longitudinal non-equilibrium plasmoid and their roles in vortex structure and dynamics. This Proposal is devoted to study of physical properties of longitudinal plasmoid created by capacity HF discharge in high-speed vortex gas flow at different gas flow parameters and capacity HF discharge parameters.
Main goals of this Proposal:
1.Study of plasma-chemical kinetics and stimulated relaxation processes in non-equilibrium longitudinal plasmoid created capacity HF discharge in high-speed vortex gas flow. Study of their roles in plasma vortex structure and its dynamics.
2.Study of regimes of a stable longitudinal plasmoid creation in high-speed vortex gas flow by capacity HF discharge.
3.Study of physical properties and parameters of longitudinal plasmoid at different gas flow parameters and electric HF discharge parameters.
4.Study of amplification and destruction of vortex by weakly ionized non-equilibrium plasma created by capacity HF discharge.
5. Study of long-lived longitudinal plasmoid creation in high-speed vortex airflow created by pulse repetitive HF discharge. Minimization of electric power input in longitudinal plasmoid.
6.Control of longitudinal plasma vortex location in space and time by additional external electrical field or external ionizer.
Modern diagnostic instrumentation will be used in this Project to study plasma and gas flow parameters, including new shadow device with excimer KrF laser, MW interferometer with high space resolution, PIV method, FTIR spectrometer, optical spectrometer, pressure sensors with high time resolution, IR pyrometer and others. Obtained results may be used in aviation, combustion, plasma physics, aerodynamics.

15. SUBJECT TERMS
EOARD, Aviation Technology, Aerodynamics

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18, NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT UNCLAS	**b. ABSTRACT** UNCLAS	**c. THIS PAGE** UNCLAS	UL	26	Stephanie Masoni, Maj, USAF
					19b. TELEPHONE NUMBER *(Include area code)* +44 (0)1895 616420

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

ISTC Project No. 3794P

Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge

Final Project Technical Report

on the work performed from 01.10. 2008 to 01.10. 2010

IHED RAS
Moscow, 127412, Izhorskaya 13/19, Russia

Project Manager **Klimov Anatoly**
Dr. Sci

Director **Fortov V.**
Academician

October 2010

This work is supported financially by <Funding Party> and performed under the contract to the International Science and Technology Center (ISTC), Moscow.

Title of the Project: Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge

Contracting Institute: IHED RAS

Participating Institutes:

Commencement Date:

Duration: 36 months

Project Manager Klimov A.

phone number: +7 (495) 485 9763

fax number: +7 (495) 4835 2283

e-mail address: klimov@ihed.ras.ru

1. Brief description of the work plan: objective, expected results, technical approach

Main Goals and Tasks of the Project #3794 (3 year duration):

1. Study of plasma-chemical kinetics and stimulated relaxation processes in a non-equilibrium longitudinal plasmoid created by capacity coupled HF discharge (CFHD) in high-speed vortex gas flow. Study of their roles in plasma vortex structure and its dynamics.
2. Study of the stable plasmoid creation regimes in high-speed vortex airflow by CHFD.
3. Study of physical properties and parameters of a longitudinal vortex plasmoid at different gas flow parameters and electric HF discharge parameters.
4. Study of amplification and destruction of vortex by weakly ionized non-equilibrium plasma created by CHFD.
5. Study of a long-living longitudinal vortex plasmoid created by pulse repetitive CHFD. Electric power minimization of HF power, required for generating of a long-living longitudinal vortex plasmoid.
6. Control of a longitudinal plasma vortex location in space and time by additional external electrical field or external ionizer.

Main Tasks of the first year:

1. Creation of a longitudinal plasmoid in high-speed vortex airflow by capacity HF discharge.

1.1. Design, manufacture and testing of HF plasma generator and vortex generator.

1.2. Study of stable regimes of longitudinal non-equilibrium plasma vortex creation by capacity HF generator. Amplification and destruction of vortex by weakly ionised non-equilibrium plasma, created by capacity HF discharge

1.3 Analysis and simulations of HF plasma and vortex airflow.

Main Tasks of the second year:

2. Study of physical properties of a longitudinal non-equilibrium plasma vortex at different airflow parameters and electric discharge parameters.

2.1. Measurement of electric discharge parameters and plasma parameters at different vortex parameters.

2.2. Study of vortex parameters at different HF discharge plasma parameters (E/N, T_e, specific energy input and others).

2.3 Analysis of experimental results and simulations of experimental results.

Main Tasks of the third year:

3. Control of longitudinal plasma vortex's location in space and its parameters by additional external electrical field and additional ionizer.

3.1. Design and manufacture of experimental set up (including external ionizer, HF generator, vortex generator, power modulator and diagnostic instrumentation).

3.2. Study of control of longitudinal plasma vortex location in space and its parameters by additional external electromagnetic field.

3.3. Analysis of experimental results and simulations of experimental results.

New knowledge expected from this Project and its influence on the future development of plasma physics and plasma aerodynamics (namely: control of vortex flow by CHFD). In the result of this Project completion will be obtained the following important information and experimental results:

1. Technical description of the plasma generator (PG CHFD) design and its testing.
2. Determination of CHFD plasma generator's operation modes for stable longitudinal plasmoid creation in vortex airflow.
3. Measuring of the plasma parameters and gas parameters in a vortex longitudinal plasmoid.
4. Control of longitudinal vortex plasmoid location by external electromagnetic field

This information is required for future development of plasma aerodynamics.

The following ***technical approaches and methodologies are used in*** this Work:

- Engineer calculations and simulations of PG's design,
- Measurements of PG's parameters and characteristics by diagnostic instrumentation during its tuning,
- Elimination of electromagnetic noise, generated by plasma, electric HF discharge and HF power modulator.

- Measurement of HF plasma parameters by diagnostic instrumentation, included the following units:
- Measurement of static pressure P_s and stagnation pressure P_o in vortex flow and vortex plasmoid by pressure transducers,
- Measurement of electron concentration N_e by electrical probes (or MW interferometer),
- measurement of temperature distribution in vortex flow behind CHFD zone by thermocouples,
- Measurement of rotation temperature T_r, vibration temperature T_v, electron temperature T_e of vortex plasmoid by optical spectroscopy method,
- Study of vortex plasmoid dynamics and airflow around it by photo camera, video camera and high-speed CCD camera with optical filters,
- Optical laser shadow system (or optical interferometer) for gas flow visualization,
- Electric shunts and calibrated resistor divider with digital oscilloscope for measuring of Volt/ Ampere Characteristics (VACh), q, discharge parameter E/N in gas discharge,
- Chemical analysis of gas flow behind plasma region (IR- spectrometer or mass spectrometer)

By means of this diagnostic instrumentation there should be measured the following plasma and airflow parameters and studied the following tasks:

- Measurement of CHFD plasma parameters in vortex flow and non-vortex flow, (N_e, T_e, $T_g(T_R)$, VACh, q, E/N and others),
- Measurements of vortex parameters ($P_{st}(t,R)$, $T_g(t,R)$, $P_o(t,R)$,…..)
- Measure of chemical composition of plasma flow,
- Temporal dynamics of vortex plasmoid ($N_e(t,R)$, $T_e(t,R)$,, $T_g(t,R)$, VACh, q, E/N and others)
- Control of plasma vortex location by external EM field.
- Recording of high-speed shadow frames of longitudinal vortex plasmoid dynamics and its structure.
- Study of stimulated relaxation plasma-chemical processes in vortex plasmoid by optical spectroscopy.

These experimental results should be obtained by diagnostic instrumentation in wide range of plasma and airflow parameters.

2. Technical progress during the three years

Nomenclature

LP	= longitudinal vortex plasmoid
HF	= high frequency
HFD	= high frequency discharge
CHFD	= capacity coupled HFD
PR	= pulsed repetitive
PR HFD	= pulsed repetitive HFD
PA	= plasma aerodynamic
F_{HF}	= HF frequency
F_M	= modulation frequency of CHFD
T_i	= pulse duration
I_{HF}	= HF electric discharge current
V_{HF}	= HF electric discharge voltage
N_{HF}	= pulse power input in plasma

V_{af} = airflow velocity
V_{ax} = axial component of the velocity
V_t = tangential component of the velocity
Q_t = tangential mass flow rate
Q_x = axial mass flow rate
P_0 = stagnation pressure
P_{st} = static pressure
T_g = gas temperature
t_{exp} = CCD camera exposure
St = Strouchal's number
$S=Q_\tau/Q_{ax}$ = swirl flow parameter

Main experimental results

1. Experimental set up WT-1 is designed, manufactured and tuned for experimental study of a longitudinal vortex plasmoid created by CHFD in swirl airflow *at high atmospheric pressure* P_{st}*~ 1 Bar*, fig.1, 2.
2. The experimental set up WT-2 is designed, manufactured and tuned to study of a longitudinal plasmoid created by CHFD in swirl flow *at low static pressure* P_{st}*< 1 Bar*.
3. HF plasma generator is manufactured and tested in experimental set up WT-1 and set up WT-2. It has the following parameters: HF frequency- F_{HF} = 13.6 MHz, HF power N_{HF}< 2 kW, operation regimes:- continuous and pulse repetitive, fig.3.
4. Swirl generator is designed, manufactured and tuned. This generator creates swirl flow in quartz duct (tube) and free space at static pressure $P_{st} \leq 1$ Bar. It is consisted of swirl chamber and ejector.
5. New diagnostic instrumentation is elaborated and arranged in the experimental set up WT-1 and set up WT-2 to study of longitudinal vortex plasmoid's parameters. It is consists of the following units and apparatus:

- Advanced optical interferometer, fig.4,
- Advanced rotated pressure probe (PP). This PP is calibrated in straight airflow with well-known parameters,
- Optical spectrometer AvaSpec 2048
- High speed CCD camera Citius,
- MW interferometer G4-108

6. It is revealed that a LP in swirl flow may be created by transverse electric DC discharge (but not CHFD only). Note that electromagnetic interference (noise) is very small in this DC discharge namely. Note that it is very important to obtain of reliable experimental data in plasma-vortex experiment. So, electric DC discharge is used in some experiments, fig.5.
7. Swirl airflow parameters are measured in set up WT-1 and set up WT-2 at plasma off and plasma on. Maximal tangential velocity in vortex airflow is about V_t~140m/s at static pressure P_{st}~ 40-100 Torr. Maximal tangential velocity V_t~30 m/s is measured in swirl flow at high static pressure about P_{st}~ 1Bar.
8. Stable vortex is created in free space in the experimental set up WT-1 at the first time, fig.9,10.
9. Vortex parameters are measured by a new rotated pressure sensor at HF plasma off and plasma on.

10. Pressure distributions are measured in swirl flow and plasmoid vortex. It is revealed that the pressure inside vortex kernel is incrased and its diameter is increased at DC plasma on. These results are depended on electric current considerably, fig.7.
11. It is revealed that there is vortex airflow attenuation (decay) at DC plasma on. There is static pressure increase in a vortex core at DC plasma on, fig.7. There is tangential velocity decrease in a vortex at DC plasma on. There is vorticity decrease at DC plasma on.
12. It is revealed that LP's parameters are closed to equilibrium ones near vortex axis. So, this *longitudinal plasmoid created by DC discharge is hot equilibrium one*. Its gas temperature is about T_g~3000K, fig.6. There is non-equilibrium plasma near electrodes (between plasma filaments) in swirl airflow only. So, excited molecules are created by transverse electric discharge near duct wall. Then there is energy release of excited molecules into thermal energy of swirl flow (in a plasmoid's cornel). In a result of this process, hot equilibrium plasma is created and concentrated in the axial region. Creation of longitudinal vortex plasmoid may be associated with V-T relaxation process (or E-T relaxation process) of exited molecules (where V- vibration energy, E- electronic energy, T- thermal energy of excited molecules). Really it is impossible to record this phenomenon in noble gas (for example, argon). Remember that creation of plasma cone is absent in vortex argon flow namely. It is necessary to study this question in detail in our experiments
13. It is obtained that LP is not created in vortex *argon flow.*
14. Very interesting LP created by transversal DC discharge is recorded in vortex nitrogen flow. Its luminescence changes from blue color near electrode zone to red- yellow one in the plasmoid's top, fig.5.
15. Airflow around a LP created by electric DC discharge in swirl flow is studied by new optic interferometer.
16. It is obtained that there is considerable temperature jump on plasmoid's surface in swirl airflow. The gas temperature is decreased from T_g~2000K inside plasmoid up to T_g~600K outside it. The typical contact surface width about 10mm, fig.8, 9. This temperature jump is measured by thermocouple also. The physics of this phenomenon is not clear today. It is necessary to continue experimental study of this phenomenon to clear the physical mechanism of *thermal insulation* of LP in swirl airflow.
17. LP is created by CFHD in swirl airflow and swirl argon flow at *low static pressure* and different mass flow rates Q, fig.10. Different LP's structures are obtained at different mass flow rates Q<10 G/s and different HF power input N_{HF}< 1 kW. It is revealed that there are co-flow plasmoid, counter- flow plasmoid and combined one. The type of LP is determined by the value Q and HF power N_{HF} namely.
18. It is revealed that a *LP created by CHFD is non- equilibrium one* (T_V~3000K> T_R~1500K), fig.11.
19. This HF longitudinal plasmoid is a hot one. Its gas temperature is about T_g~1400÷1500K near vortex axis. Note that these results are correlated with the ones obtained by DC discharge.
20. It is interesting result is obtained in argon swirl flow at CHFD plasma on. Plasmoid has different luminescence color before HF electrode and behind it. It is revealed that there is optical spectrum of pure argon in the region before HF electrode and pure nitrogen behind it.
21. It is revealed that there is vortex decay (destruction) at CHFD plasma on. Static pressure near vortex axis is increased up to 50% at CHFD plasma on, fig.13, 20, 21.

22. Velocity V_p of LP top's propagation is measured in swirl flow by high speed camera at *low static pressure.* The typical value V_p is about 30÷40 m/c and does not depend on swirl flow velocity.
23. The optical spectra of LP's luminescence are obtained at different swirl flow parameters, different HF power and different *low initial pressure* $P_{st}=40÷400Torr$. These obtained optical spectra are processed. A non-equilibrium plasma formation is created by CHFD in vortex nitrogen flow (T_V ~ 3200 ± 400 K, T_{rot}~ 1000÷1600K). It is revealed that there is energy exchange between internal energy levels of exited nitrogen molecules and translation energy of these molecules in a longitudinal plasmoid (V-T relaxation process).
24. Longitudinal plasmoid created by a *transversal CHFD* in swirl flow is studied in the set up WT-2, fig.16-18. Note that this study is important for different aviation applications namely.
25. It is revealed that plasmoid's parameters in vortex gas flow created by *a transversal CHFD* are closed to the one in ambient motionless gas. So, gas dynamic drift of this plasma formation by gas flow is absent (or very small) in this regime. Note, that these experimental results are contradicted with the ones created by transverse DC discharge or longitudinal HF discharge obtained in our previous reports [1, 2]. The answer for this question is absent now.
26. Optical spectra of a LP created by *a transversal CHFD* are obtained and processed, fig.19. The following results are obtained:
    - Rotation temperature in HF plasma formation T_R= 600K,
    - Vibration temperature in HF plasma formation Tv=3000K.

    So, there is a non-equilibrium plasma formation created by this HF discharge in swirl airflow. Note that gas temperature T_g~T_R is not high in this regime comparing with the one measured in LP created by a longitudinal HF discharge (T_g~ 2000K, see [2,3]).
27. Pressure distribution measurements are obtained in a LP created by a transversal CHFD and the one created by longitudinal HF discharge, fig.20, 21.
28. It is revealed that pressure gradient is absent near vortex axis at plasma on. So, there is no gas flow inside central vortex region (part). One can suppose that there is vortex decay (its destruction) at plasma on. It is needed to study this suggestion in detail in our future experiment.
29. HF power modulator is designed, manufactured and tested. This modulator has the following parameters: Maximal modulation frequency is about 2 kHz
    - HF frequency F_{HF}=0,5 MHz
    - Modulation frequency F_M<2 kHz
    - Pulse duration T_i<10ms
    - Pulse HF power N_{HF}<2kW
30. Different non-equilibrium LPs in swirl flow are obtained by *pulse repetitive HF discharge* both the homogeneous ones and non-homogeneous ones. These plasma formations are depended on vortex parameters dramatically.
31. Axial pressure in swirl flow is measured at plasma on and plasma off and different HF discharge parameters (power modulation parameters). These measurements are obtained at high static pressure (P_{st}~1 Bar) and low static pressure (P_{st}~100 Torr).
32. Longitudinal HF plasmoid inside of a free conical vortex behind aerodynamic model (plate model at different attack angle) is created and studied in open airflow at the first time. It is revealed that HF plasma destructs this vortex effectively.
33. LP creation and its structure in a swirl flow *at pulsed repetitive HF power pumping* are studied by high-speed camera and optical interferometer *at the first time*, fig.22, 23. It is

revealed, that longitudinal HF discharge creates a hot cavern near vortex axis. The secondary HF filaments propagate in this hot cavern created by preliminary plasma filaments in pulsed repetitive HF power pumping regime.

34. LP's propagation velocity is closed to the typical axial velocity of counter (reverse) swirl flow Vs~10-30 m/s, fig.24.
35. A longitudinal homogeneous plasmoid in free swirl flow is created by CHFD in open atmosphere at the first time. There is a compact homogeneous constricted longitudinal plasmoid in swirl flow at high modulation frequency $F_M > F_M^{*} \sim 1kHz$ only.
36. Swirl flow control by CHFD is studied in this work. It is revealed that free vortex in open atmosphere is destructed by CHFD plasma effectively at $F_M > F_M^{*} \sim 1\ kHz$ (or $St \geq 2\text{-}3$) namely. The detail shadow pictures of free vortex destruction by longitudinal plasmoid created by CHFD at different flow velocity are obtained and analyzed, fig.25.
37. It is revealed that there is a number of resonant modulation frequencies (F_M^{*}=3.45 kHz; 5.9 kHz and others) of strong LP-vortex interaction. Intensive acoustic waves are created by CHFD in swirl flow in this regime.
38. Study of control of a longitudinal plasma vortex location in space and by additional external electromagnetic field is started. It is revealed that it is possible to change LP position in swirl flow by external DC electric field.
39. Numerical results on a LP's structure and its evolution are obtained and compared with experimental results. Simple plasma-chemical kinetics is used in this numerical study. It is shown that there is good agreement between experimental results and theoretical ones
40. The pressure distributions measured on the wedge surface and duct wall are measured at HF plasma on and HF plasma off and different airflow velocity of incoming airflow. There is pressure increase of wall pressure about of 20-25 %. This result proves that there is vortex decay (attenuation) by HF plasma. The additional experiments with small helium jet injection prove the conclusion about vortex attenuation by a longitudinal HF plasmoid also.
41. Detail optical spectra with a high space resolution are obtained in this work. Processing of these spectra gives us important information about non- equilibrium plasma parameters of a longitudinal plasmoid created by CHFD in swirl flow, fig.26

3. Current technical status

1. All tasks are fulfilled now

4. Cooperation with foreign collaborators/partners

- trips to/from foreign collaborators/partners
- workshops, topical meetings organized by the project team
- joint attendance to international conferences

5. Problems encountered and suggestions to remedy

No problems

6. Perspectives of future developments of the research/technology developed

New ISTC Proposal named “Flow Control Around Body by Longitudinal Plasmoid Created by Capacity Coupled HF Discharge” is prepared. This Proposal is continuation of present ISTC Project #3794P

Attachment 1: Illustrations attached to the main text

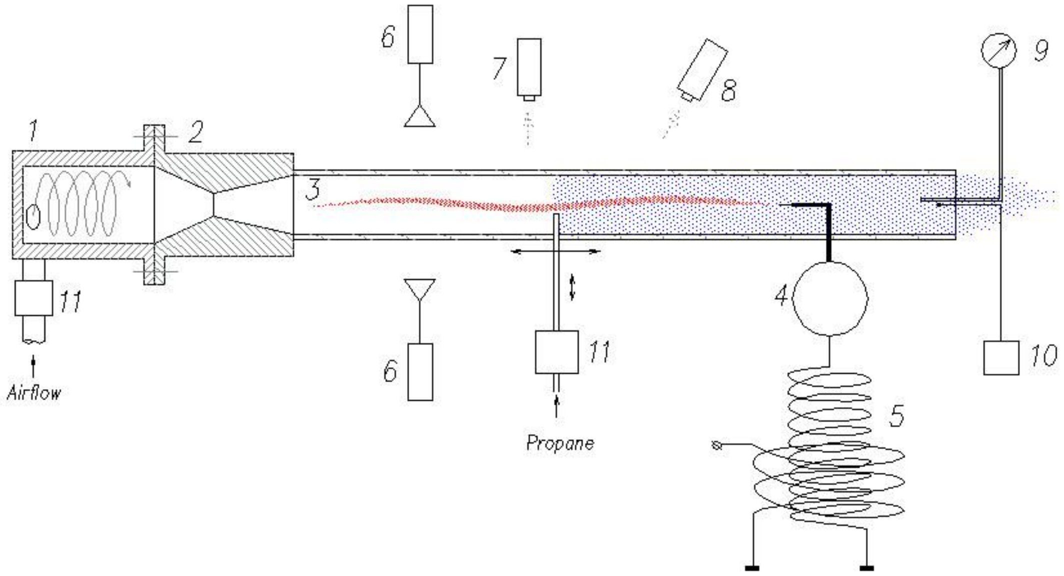


Fig.1. Scheme of the experimental set up SWT-1 with vortex chamber (1): *2- nozzle, 3-quartz tube, 4- HF ball electrode, 5- Tesla’s transformer, 6- microwave interferometer, 7- video camera, 8-optical pyrometer, 9-pressure sensor, 10- thermocouple*

Fig.2. General view of experimental set up SWT-1

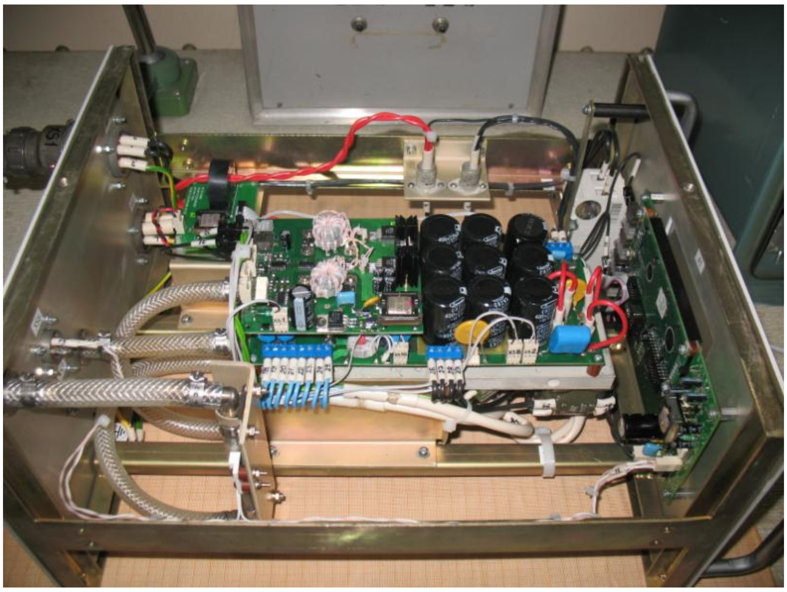


Fig. 3. The assembly of HF power supply

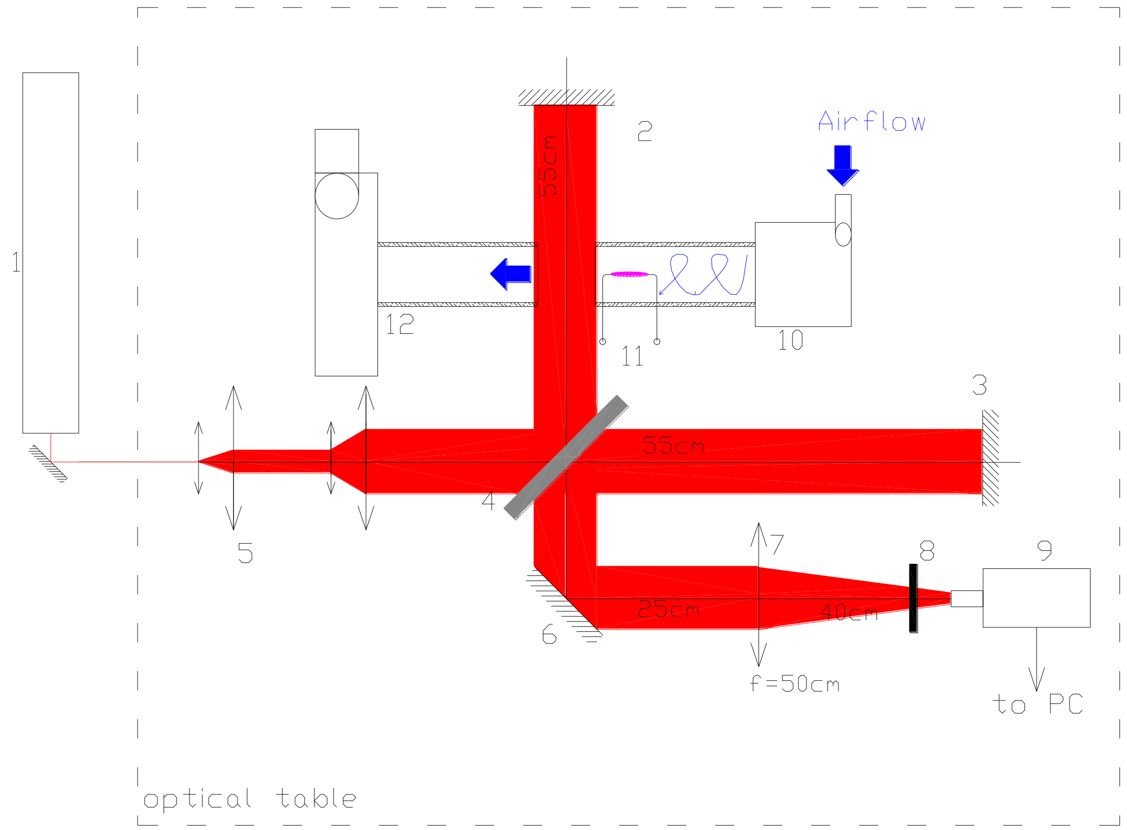


Fig.4. Scheme of the optic interferometer with swirl chamber (10): *1- laser LGN-315, 2,3,4,6- mirrors, 5- optical collimator, 7- lens, 8- optical filter, 9- high-speed videocamera Citius, 10- swirl (vortex) generator with quartz tube, 11-electrodes, 12-suction gas dynamic device with quarth tube*

Fig.5. Plasma filaments and plasma cone in vortex nitrogen flow (integral photos). *DC discharge, I_d=2Amp. The view along axis of test section (left) and lateral view (right). Q=9G/s, D_{el}- 58mm, D=60mm*

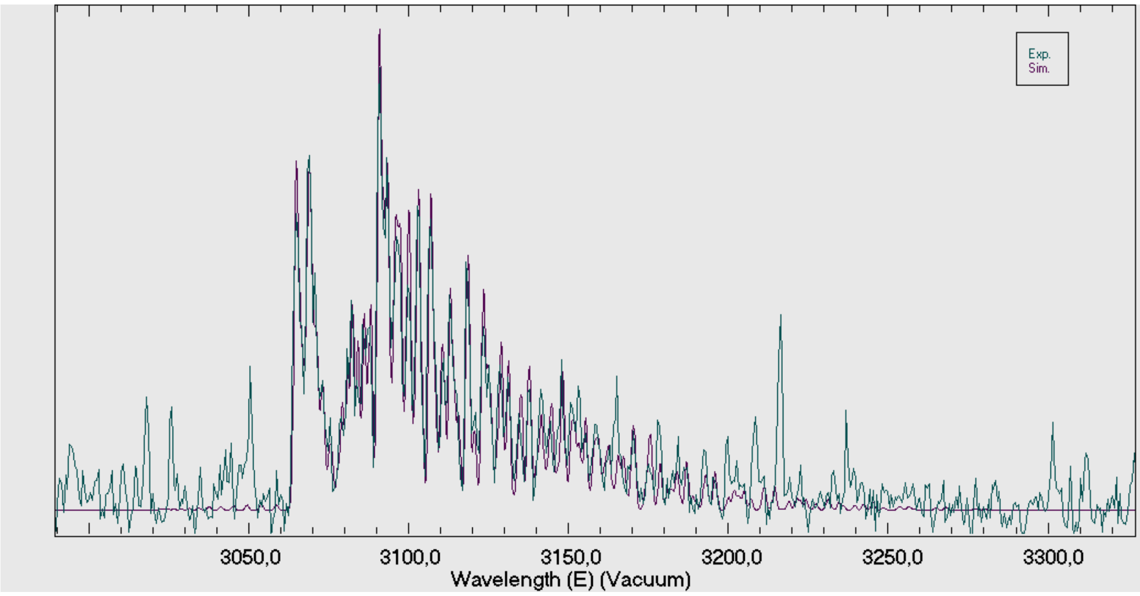


Fig.6. Experimental optical spectrum obtained in plasma vortex (see. Fig.5, blue) and simulated spectrum (violet). *The gas temperature is about T_g~3000K*

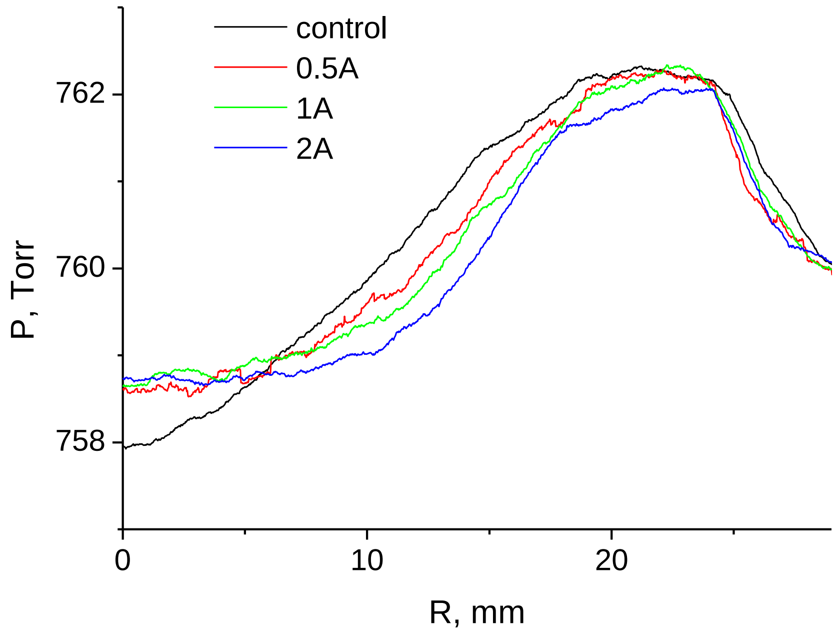


Fig.7. Dependence of tangential stagnation pressure on different electric DC discharge current at the cross section X= -6cm (X=0- location of electrodes)

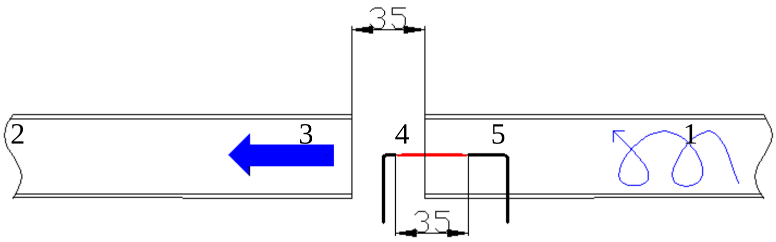


Fig.8. Scheme of plasma-vortex experiment. *1-vortex generator, 2- section device, 3- gap, 4, 5- electrodes*

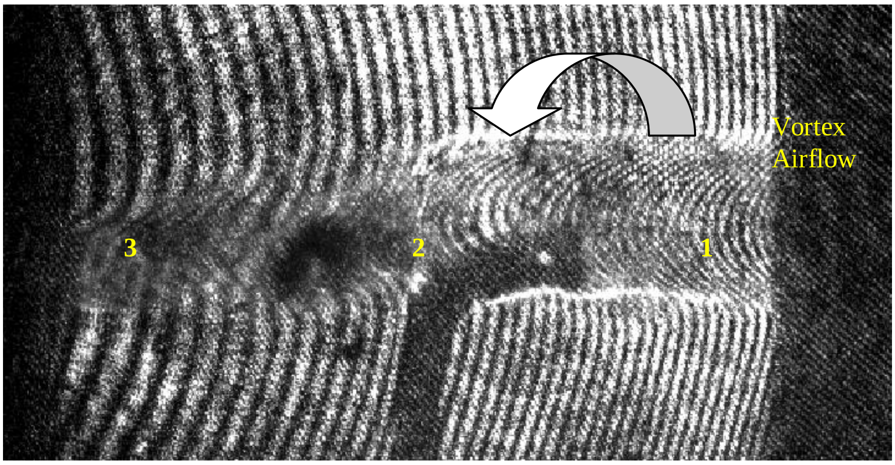


Fig.9. Airflow (hot wake) behind down electrode (2). *Airflow axis velocity -1m/s, tangential velocity ~30m/s, static pressure –P_{st}~1Bar, N_d~0,150 kW. 1- plasma formation, 2- electrode, 3- hot wake*

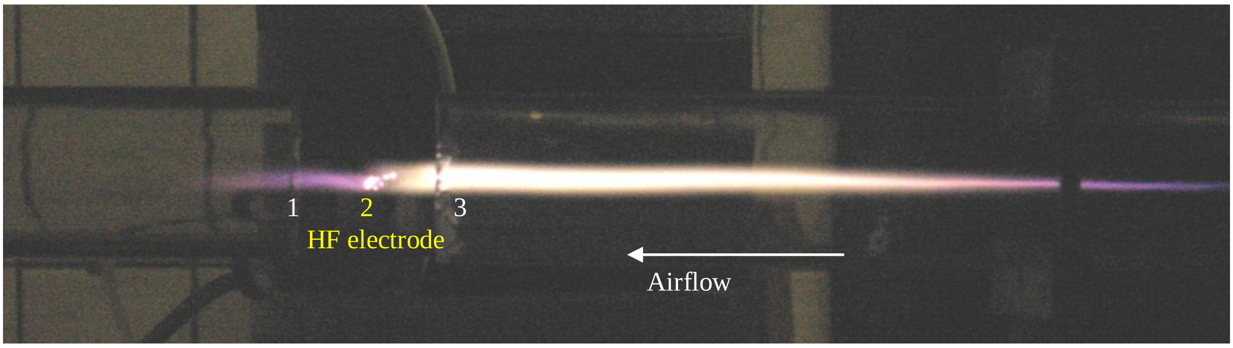
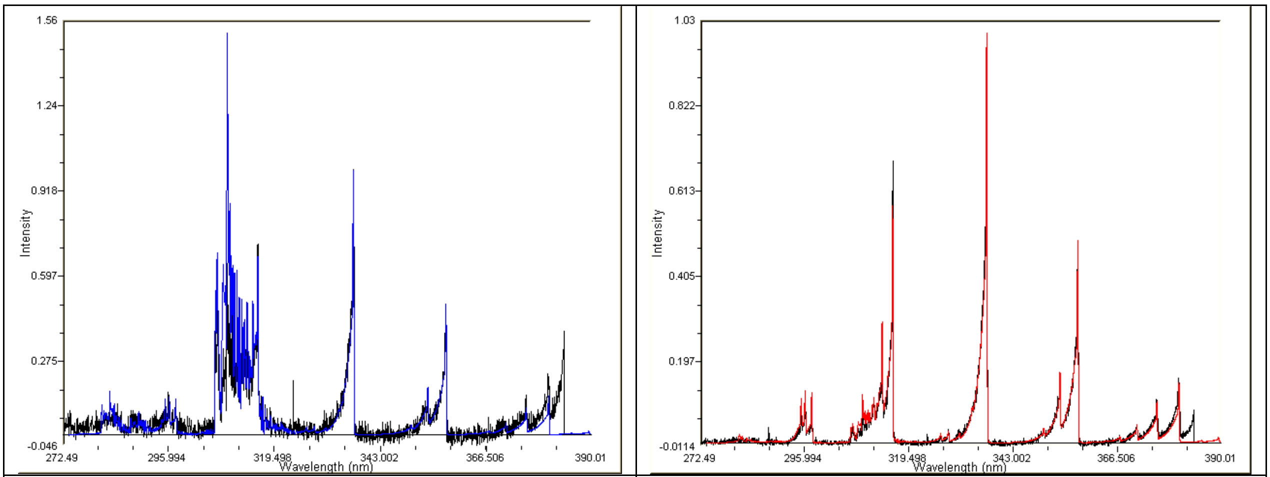


Fig.10. Longitudinal vortex plasmoid created by capacity HF discharge between two quartz tubes. *1, 3- quartz tubes, 2- "hot" HF electrode*



25cm before HF electrode. T_R=1500K, T_V=3500K | 5cm behind HF electrode, T_R=1400K, T_V=3500K.

Fig. 11. Optical spectra in longitudinal vortex plasmoid created by capacity HF discharge. *Vortex airflow, P_{st}~1 Bar, N_{HF}~600W, tube diameter~40 mm, Q~8 G/s*

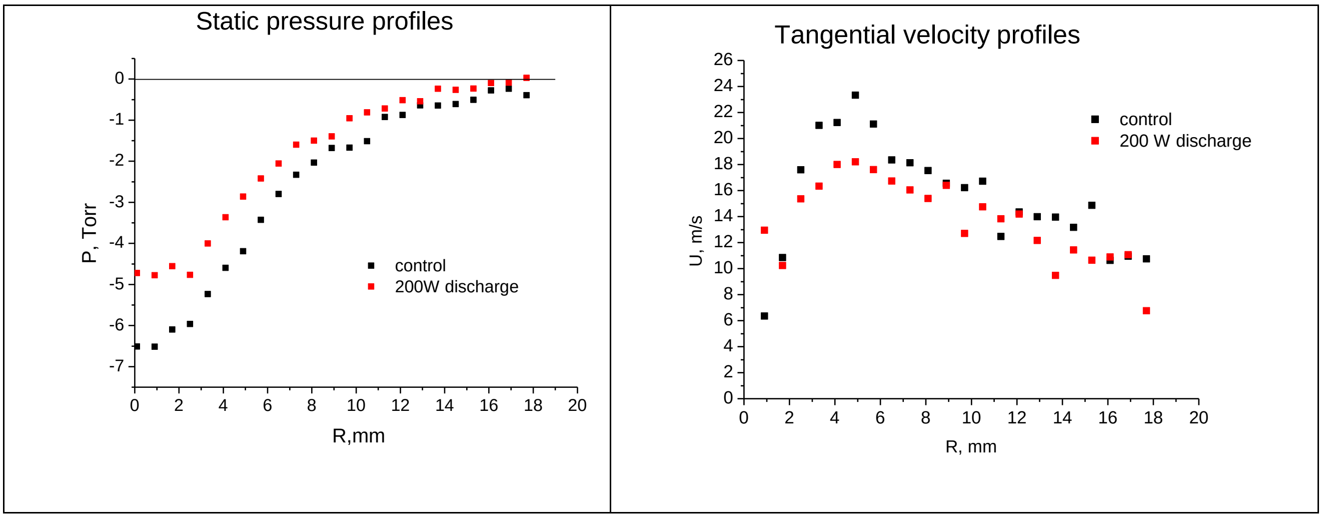


Fig.12. Static pressure distribution and tangential velocity distribution in vortex airflow at plasma off (black points) and plasma on (red points)

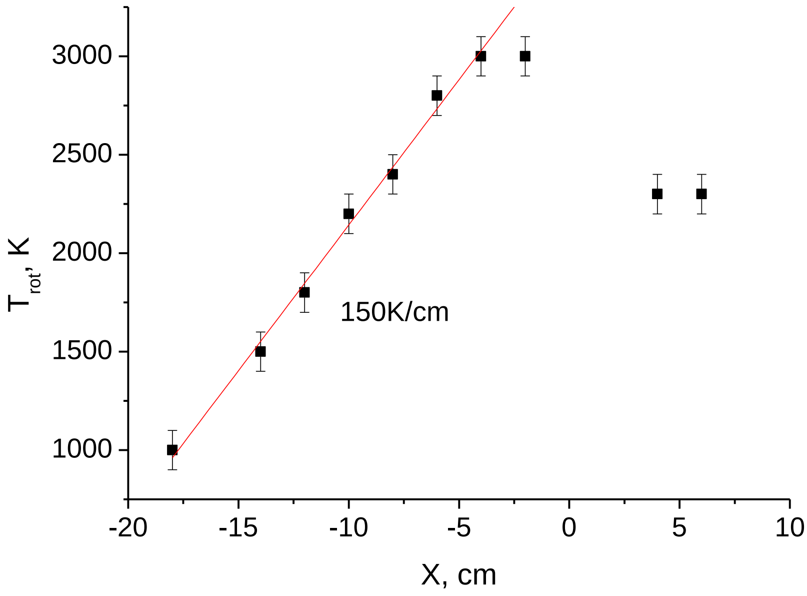


Fig.13. Rotational temperature distribution T_{rot}(X) along plasmoid's axis. *Nitrogen flow, P_{st}~40 Torr, N_{HF}~1200W, Q=1 G/s*

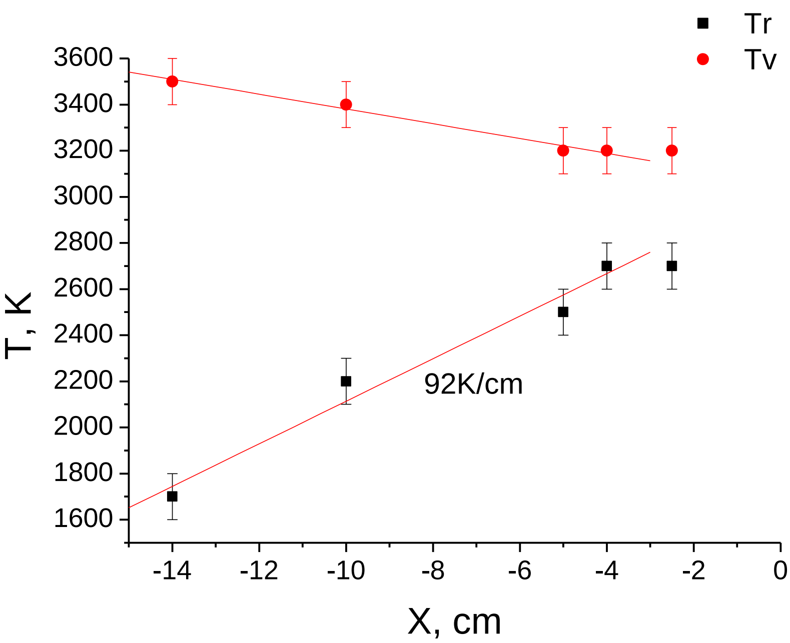
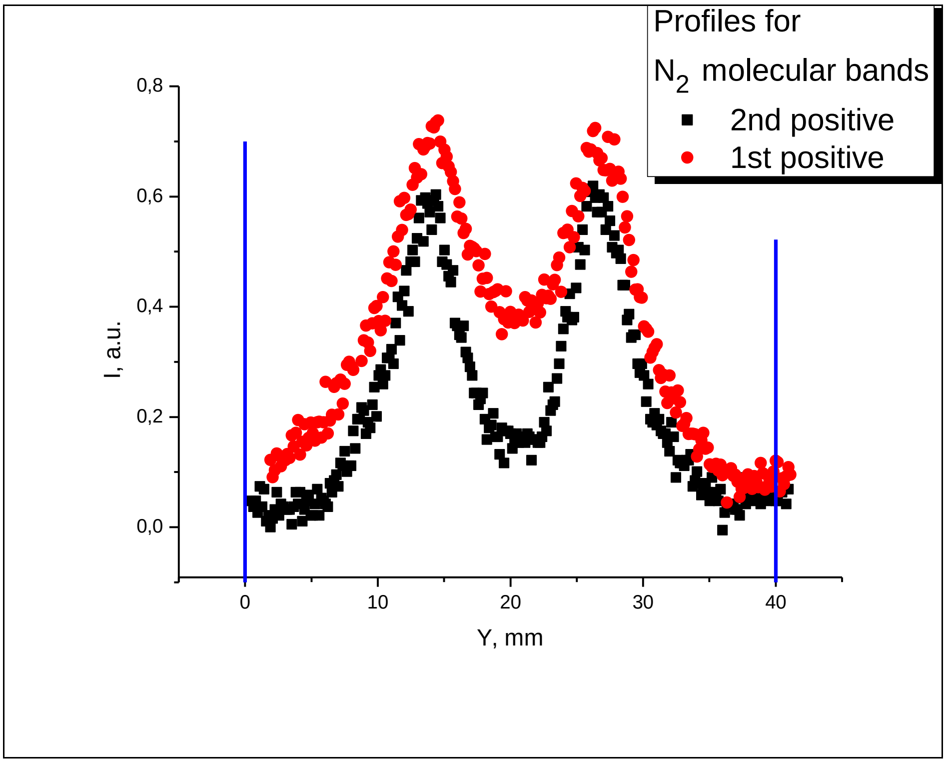
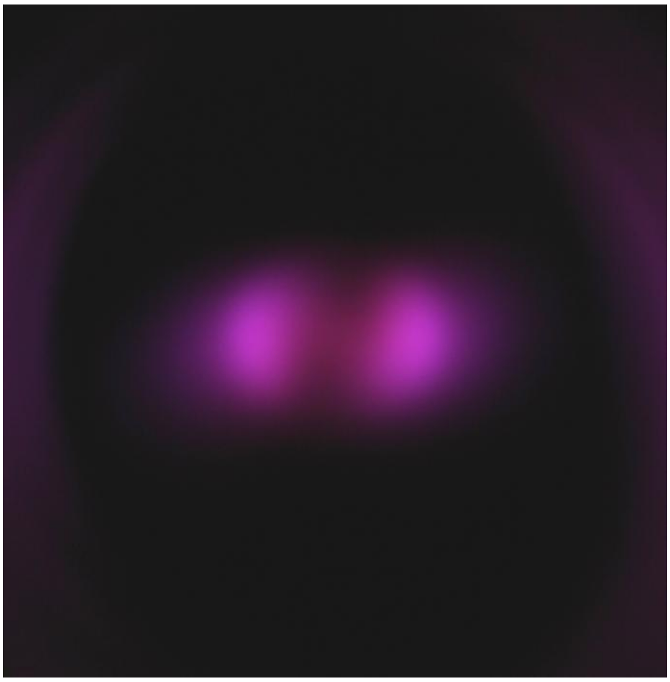


Fig.14. Rotational temperature distribution T_{rot}(X) and vibration temperature distribution T_V(X) along plasmoid's axis. *Airflow, P_{st}~40 Torr, N_{HF}~1200W, Q= 0,6 G/s*



a.

Fig.15. Normalized molecular band intensities $I_{1st}(R)$ and $I_{2nd}(R)$ of luminescence of vortex plasmoid created by transverse HF discharge



b.

Fig.16. Transverse HF discharge luminescence, *b).- top view. Q= 4G/s N_{el}= 1.7kW, P_{st}= 40Torr*

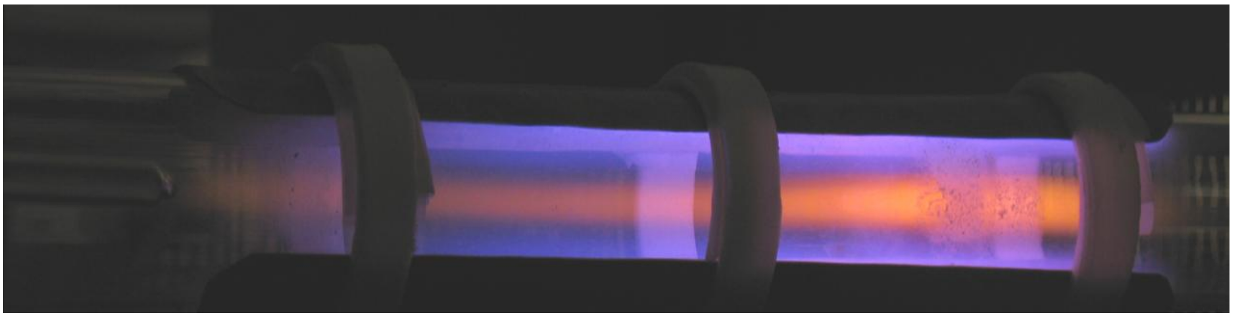
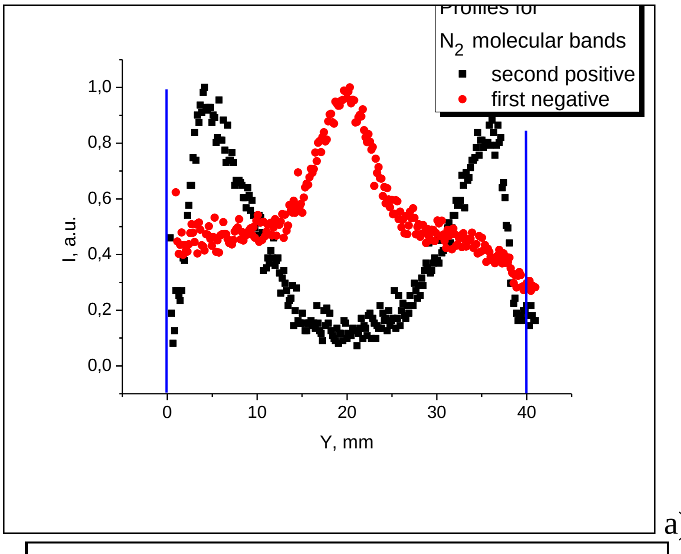
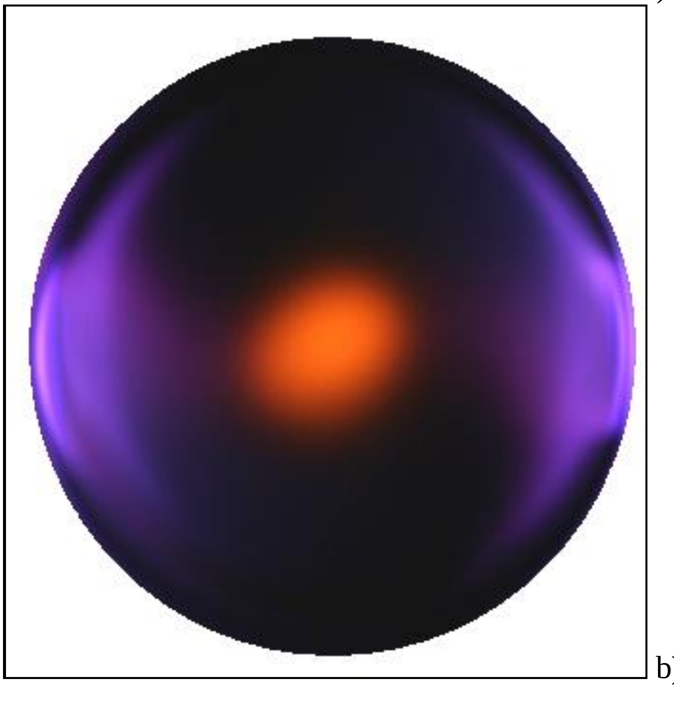


Fig.17. Plasma formation in N2 vortex flow. Transversal capacity HF discharge. Cross section view –top. Lateral view -down. *Q=4G/s* N_{HF}*=1.7kW,* P_{st}*= 40Torr*



a).



b).

Fig.18. - a).- Normalized intensity profiles for different N2 molecular bands, b.) transverse capacity HF discharge- top view. *Q=4Gg/s* N_{el}*=1.7kW, P=40Torr*

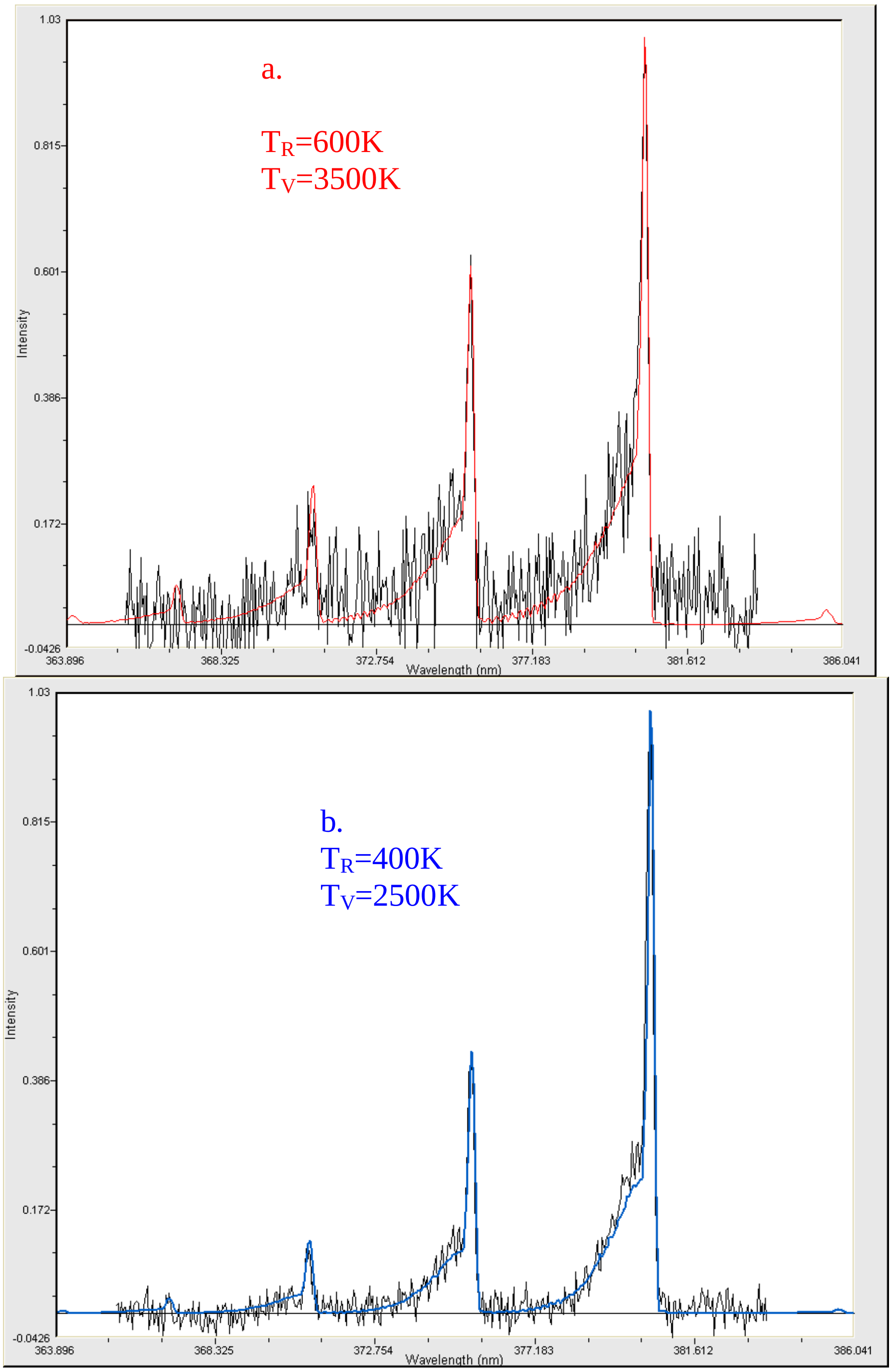


Fig. 19. Processing of optical spectra recorded in wall plasmoid (b) and central plasmoid (a) created by transversal HF discharge in N2 vortex flow. *Q=4G/s N_{el}=1.7kW, P=40Torr*

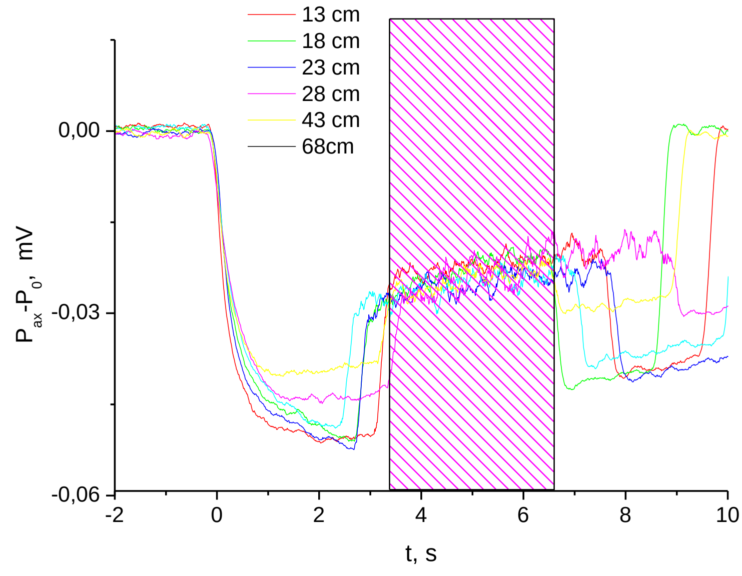


Fig.20. Pressure sensor signals in different duct ports. Transversal HF discharge in vortex airflow. *Q= 4.5 G/s, N_{el}= 2.5 kW, P_{st}= 40 Torr. HF plasma location is shown by magenta window*

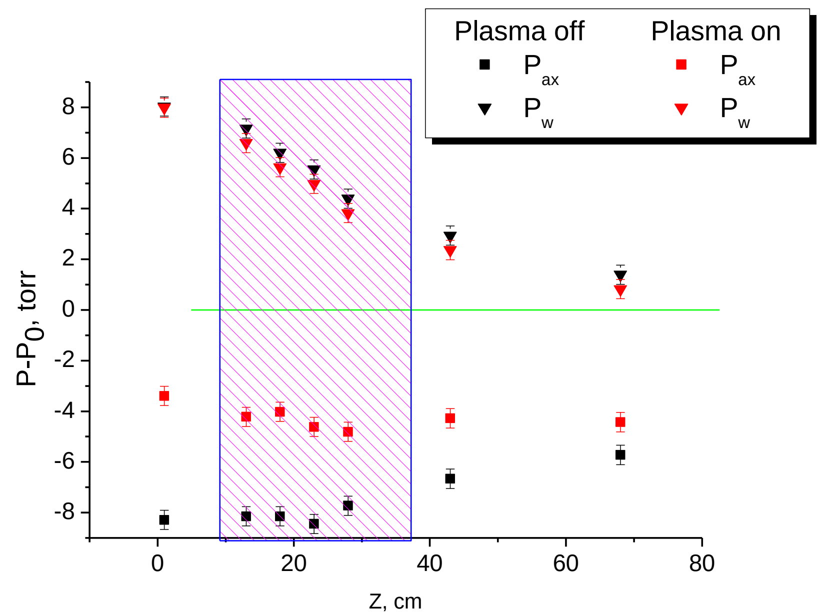


Fig.21. Static pressure distribution in vortex airflow. Transversal HF discharge, *Q= 4.5G/s, N_{el}= 2.5kW, P_{st}= 40Torr, electrode position is marked by a blue window, plasma region- magenta shading*

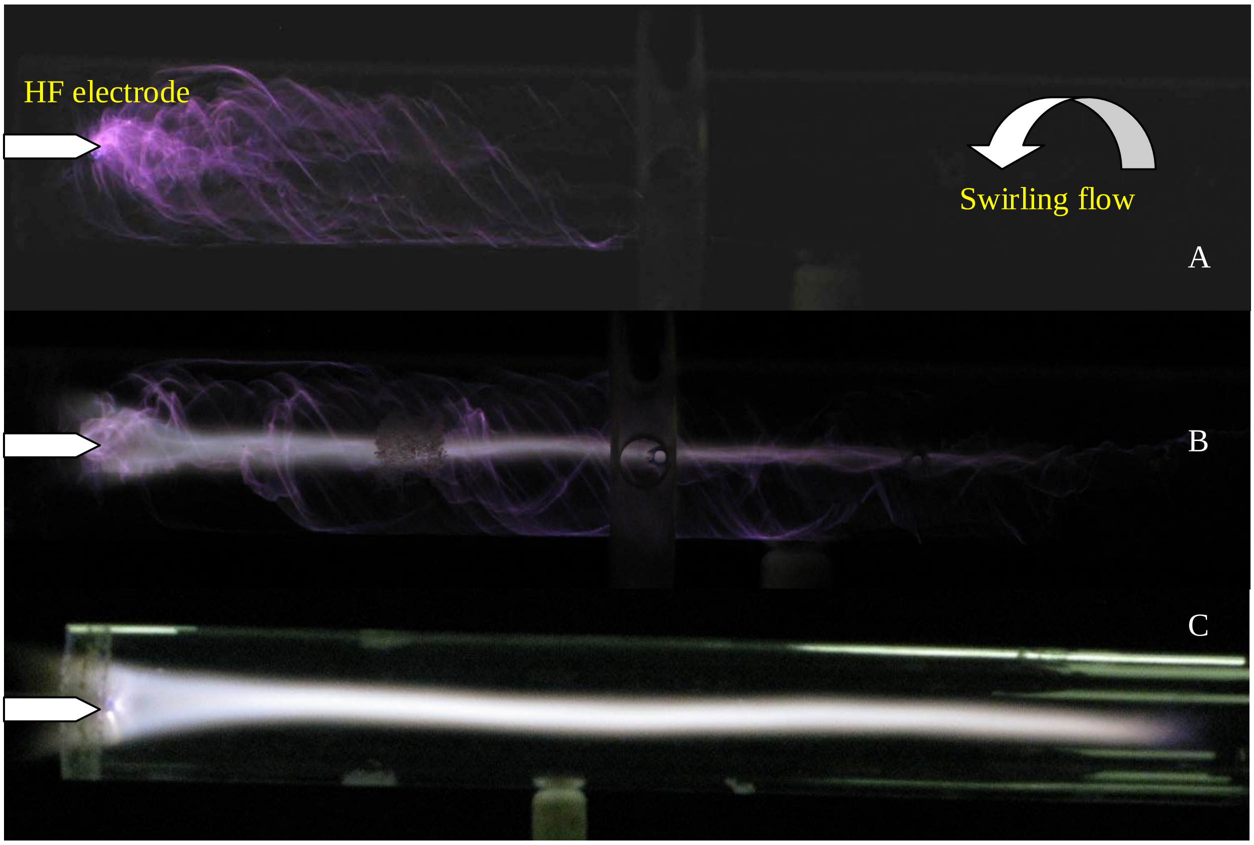


Figure 22. Different regimes of LP creation by HF discharge. *Pulse duration t=1ms, modulation frequency F_M=500Hz, P_{st} =1 Bar. A- HF streamer discharge Q_t=2G/s, Q_z=4G/s; B- transient regime Q_t=4G/s, Q_z=7G/s; C- stable LP creation regime Q_t=4G/s, Q_z=2G/s*

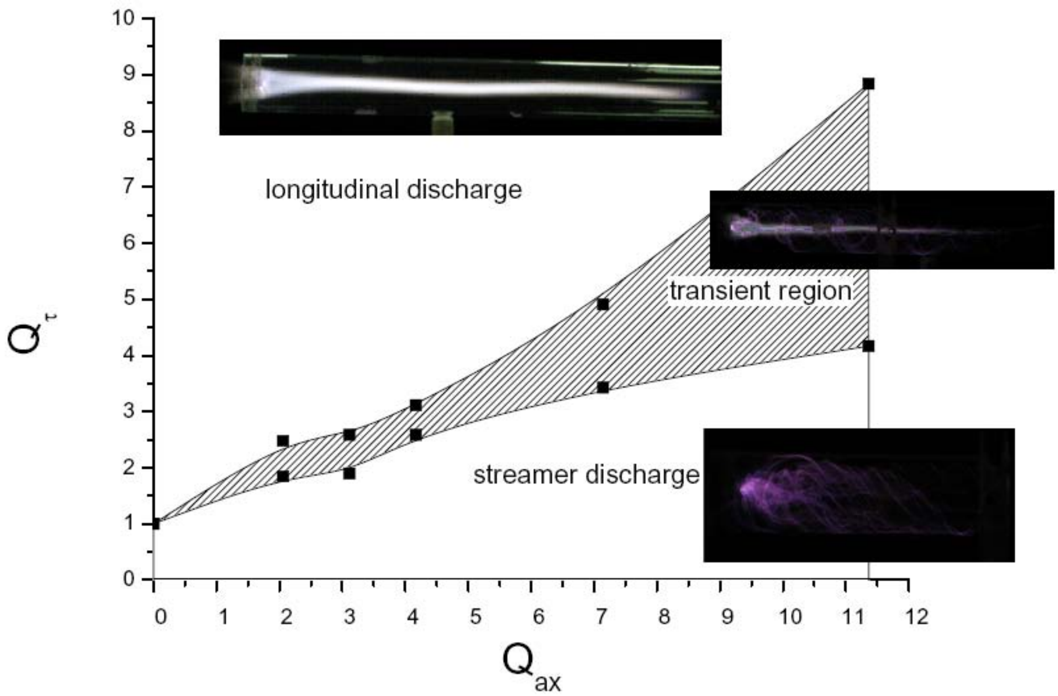


Figure 23. LP regimes at different vortex parameters. *Pulse duration t=1ms, modulation frequency F_M=500Hz, P_{st} =1 Bar. A- HF streamer discharge Q_t=2G/s, Q_z=4G/s; B- transient regime Q_t=4G/s, Q_z=7G/s; C- stable LP creation regime Q_t=4G/s, Q_z=2G/s*

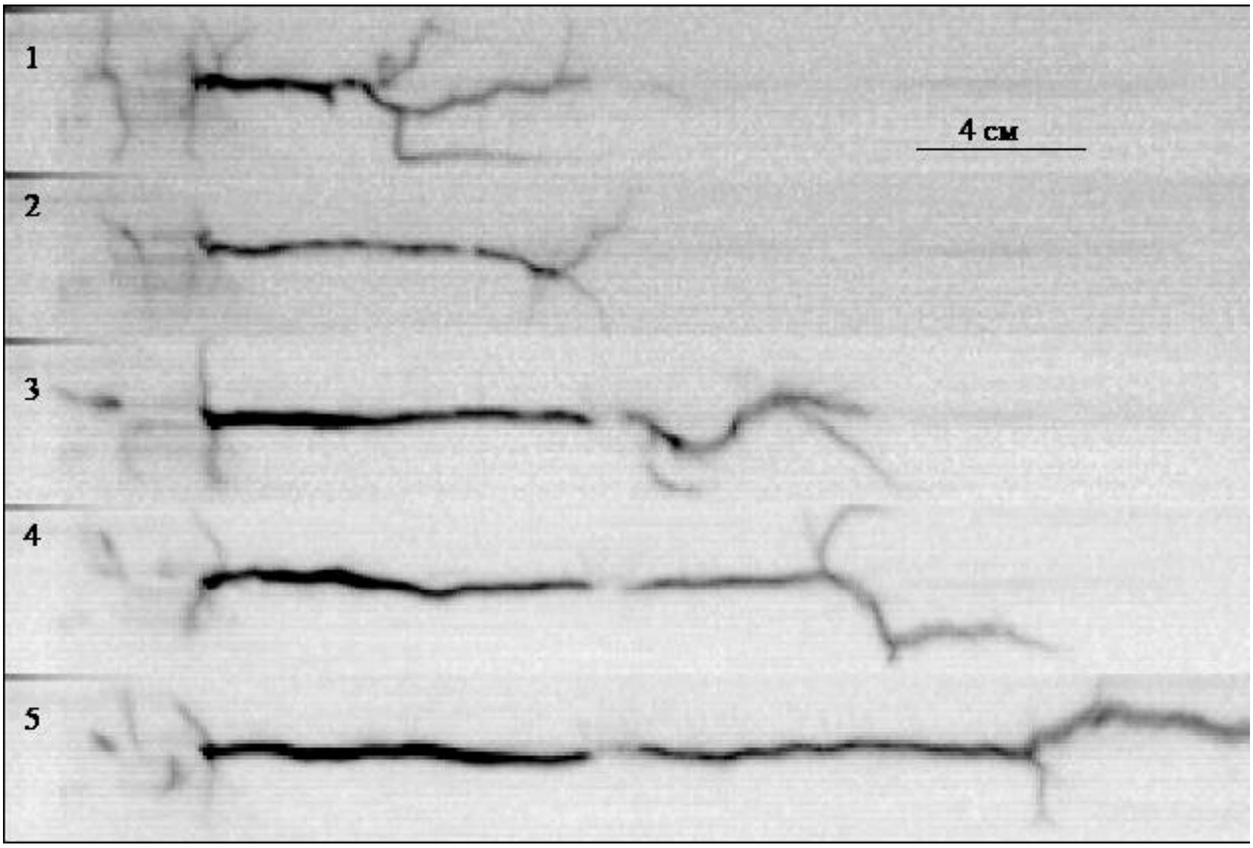
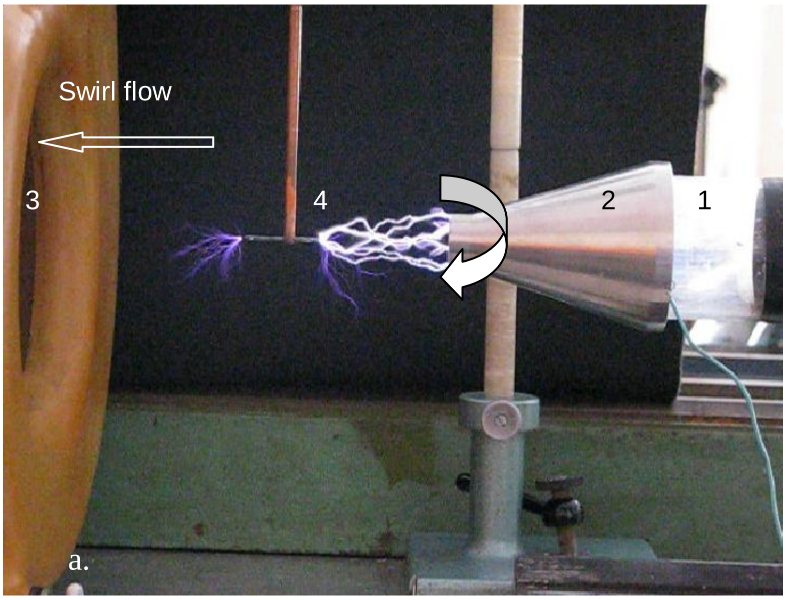


Figure 24. The frames of high-speed video of LP's propagation in a swirl flow. *Modulation frequency F_m=250Hz, τ=0.5ms. V_t~20 m/s, V_{ax}~ - 8 m/s. U~20kV, t_{exp}=300us.*



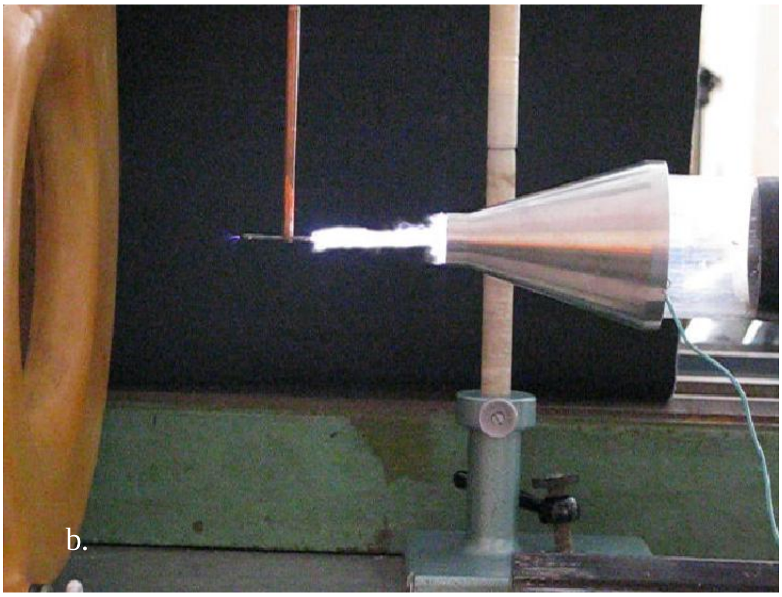


Figure 25. CHFD in swirl airflow. *F_M ~ 0.8kHz- a., F_M ~ 2kHz- b.; V_t~V_x~30m/s, P_{st}~1 Bar.1-swirl generator, 2-nozzle, 3-ejector, 4- HF electrode. Lateral view*

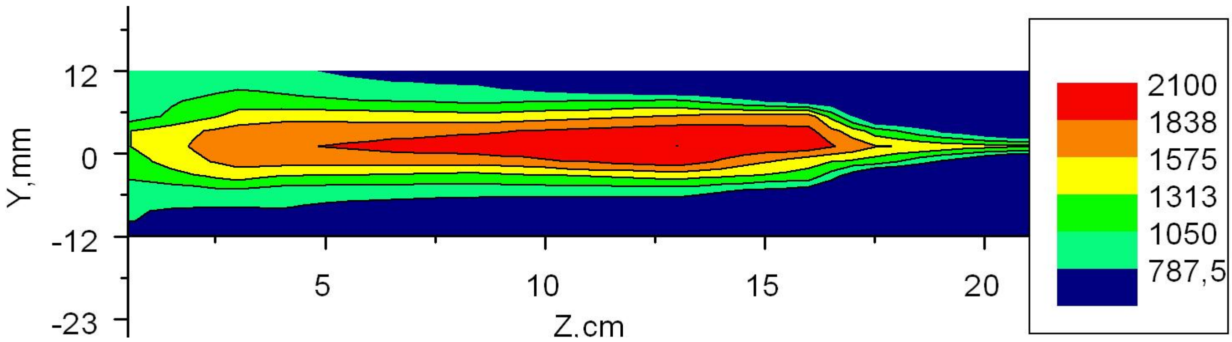


Figure 26. The typical space gas temperature distribution in HF plasmoid. *Q_t~4.5G/s. I_{HF} =168mAmp, <P_{HF}>=240W*

Attachment 1: Illustrations attached to the main text (if)
Attachment 2: Other Information, supplements to the main text
Attachment 3: Abstracts of papers and reports published during the year of reference

1. Klimov A., Moralev I., et.al., **Longitudinal Vortex Plasmoid Created by Capacity HF Discharge,** AIAA Paper, Proc. 45th AIAA Conf. Reno NV, 7-11 Jan 2008, P.11

Plasma-shock wave interaction, plasma-acoustic wave interaction and plasma-aerodynamics were studied in many works (see, for example, [1]). Unfortunately vortex structure and its dynamics in non-equilibrium weakly ionised plasma are studied insufficiently (or non-detail) today. This task is very important for possible application in aviation and plasma-assisted combustion [1-6]. Remember that a stable longitudinal plasmoid (up to 2m) is created by sub-critical electric HF field in high-speed vortex airflow (M~0.8; P_{st}~1 Bar) in our experiment at the first time [3]. High voltage HF plasma generator (Tesla's coil HF plasma generator) is used to create this longitudinal plasmoid in high-speed vortex airflow. The typical parameters of this capacity HF plasma generator are the following: maximal output voltage ~ 60kV, HF power ~ 1-10 kW, HF frequency- 0,5-1 MHz. Main tasks studied in this work are the followings: 1.Plasma-chemical kinetics and stimulated relaxation processes in non-equilibrium longitudinal plasmoid created capacity HF discharge in high-speed vortex airflow. 2.Dependence of plasma vortex structure and its dynamics on stimulated relaxation plasma-chemical processes. 3.Amplification and destruction of vortex by weakly ionized non-equilibrium HF plasma.

Plasma and airflow parameters are measured by different diagnostic instrumentation including shadow optical device with excimer KrF laser, MW interferometer, electric and current probes, optical spectrometer, high-speed CCD camera, and others.

The following main new experimental results are obtained in this work: 1.Gasdynamic and plasma parameters in vortex plasmoid are measured. 2. Structure and dynamics of vortex plasmoid are studied at different electric discharge parameters.

Detail optical spectra are recorded in different cross sections of the vortex plasmoid at different operation modes of plasma generator. These spectra are processed and analyzed. Non-equilibrium processes in vortex plasmoid are studied.

2. Klimov A., Bitiurin V., et.al., **Study of Longitudinal Plasmoid Created by Capacity HF Discharge in Vortex Airflow**, AIAA Abstr. 47th AIAA Conf. Orlando, FV, 7-11 Jan 2009, P.11

Vortex plasmoid structure and its dynamics are studied insufficiently (or non-detail) today. This task is very important for possible application in aviation and plasma-assisted combustion.

Remember that a stable longitudinal plasmoid (up to 2m) is created by sub-critical electric HF field in high-speed vortex airflow (M~0.8; P_{st}~1 Bar) in our experiment at the first time. High voltage HF plasma generator (Tesla's coil HF plasma generator) is used to create this longitudinal plasmoid in high-speed vortex airflow. Main tasks studied in this work are the followings:

1. Plasma-chemical kinetics and stimulated relaxation processes in non-equilibrium longitudinal plasmoid created capacity HF discharge in high-speed vortex airflow.
2. Amplification and destruction of vortex by weakly ionized non-equilibrium HF plasma.
3. Measurement of vortex plasmoid's parameters and vortex gas flow parameters in wide range of HF discharge parameters at different static pressure

Experimental set up LVP-1 is manufactured, tested to study of longitudinal vortex plasmoid created by capacity HF discharge or DC discharge. The typical parameters of this capacity HF plasma generator used in experiment are the following: maximal output voltage ~ 60kV, HF power ~ 1-10 kW, HF frequency- ~13,6 MHz.

Plasma and airflow parameters are measured by different diagnostic instrumentation including shadow optical device with excimer KrF laser, optical interferometer with high-speed camera Citius, MW interferometer, electric and current probes, optical spectrometer and others. on. There is vorticity decrease at plasma on. The following main new experimental results are obtained in this work:

1. Airflow around vortex plasmoid is studied at wide range of gas dynamic parameters and plasma parameters.
2. Hot wake behind plasmoid is studied by optical interferometer and thermocouples simultaneously. It is obtained that there is considerable temperature jump on plasmoid's surface in vortex airflow. The gas temperature is decreased from T_g~2000K inside plasmoid up to T_g~600K outside it. This temperature jump is measured by thermocouple also. The physics of this phenomenon is not clear today. It is necessary to continue experimental study of this phenomenon to clear the physical mechanism of thermal insulation of a longitudinal plasmoid in vortex airflow.

The typical interferometer frames of vortex plasmoid and hot gas flow wake behind this plasmoid created by longitudinal electric DC discharge are shown in fig. 1-5.

The typical interferometer frames of non-vortex plasmoid and hot gas flow wake behind plasmoid created by longitudinal electric DC discharge are shown in fig. 3-4. One can see that there is longitudinal turbulent hot wake behind down electrode in this regime.

3. Detail optical spectra are recorded in different cross sections of vortex plasmoid at the different operation modes of HF plasma generator or DC plasma generator, fig.5. Non-equilibrium processes in vortex plasmoid are studied. The typical optical spectra obtained in vortex airflow are shown in fig. 6, 7. One can see that there are OH molecular band and NO continuous spectrum in plasma region#2 (between electrodes). There are the N_2 2^+, N_2^+ 1^-, CN A-X molecular bands in plasma region #1 near cathode. These spectra were processed. The simulated spectra (blue and red) and experimental ones (black) are shown in fig. 7. One can see that these spectra are closed to each other. Rotation temperature Tr~2000-3000K and vibration temperature Tv~ 3000K are estimated from these spectra. It is very important that T_r~T_v. So, there is equilibrium plasma formation near vortex axis.
4. It is revealed that a longitudinal vortex plasmoid has a complex structure. Non-equilibrium plasma is created in the distant regions from hot HF electrode (T_V~3000K> T_R~1500K) and equilibrium one is created in the vortex axis region near HF electrode. Measured gas temperature is about T_g~2000-3000K in this region.
5. It is obtained that creation of a longitudinal vortex plasmoid may be associated with V-T relaxation of exited molecules. This longitudinal vortex plasmoid is not created in noble gas (for example, argon).
6. It is revealed that there is vortex airflow attenuation (decay) at plasma on. There is static pressure increase in a vortex core at plasma on. There is tangential velocity decrease in a vortex at plasma
7. Structure and dynamics of vortex plasmoid are studied at different electric discharge

parameters.

Quarterly Reports

1. Quarterly ISTC Report., Delivery No 1., Project #3794P, Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge, JIHT RAS, 31 Dec 2007, P.37
2. Quarterly ISTC Report., Delivery No 2., Project #3794P, Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge, JIHT RAS, 25 March 2008, P.27
3. Quarterly ISTC Report., Delivery No 3., Project #3794P, Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge, JIHT RAS, 25 June 2008, P.41
4. Annual ISTC Report., Delivery No 4., Project #3794, Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge, JIHT RAS, 25 September 2008, P.25
5. Quarterly ISTC Report., Delivery No 5., Project #3794P, Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge, JIHT RAS, 25 December 2008, P.32
6. Quarterly ISTC Report., Delivery No 6., Project #3794P, Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge, JIHT RAS, 25 March 2009, P.21
7. Quarterly ISTC Report., Delivery No 7., Project #3794P, Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge, JIHT RAS, 25 June 2009, P.32
8. Annual ISTC Report., Delivery No 8., Project #3794P, Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge, JIHT RAS, 25 September 2008, P.37
9. Quarterly ISTC Report., Delivery No 9., Project #3794P, Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge, JIHT RAS, 25 Dec 2009, P.32
10. Quarterly ISTC Report., Delivery No 10., Project #3794P, Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge, JIHT RAS, 25 March 2010, P.27
11. Quarterly ISTC Report., Delivery No 11., Project #3794P, Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge, JIHT RAS, 25 June 2010, P.21
12. Quarterly ISTC Report., Delivery No 12., Project #3794P, Longitudinal Plasmoid in High-Speed Vortex Gas Flow Created by Capacity HF Discharge, JIHT RAS, 25 Sept 2010, P.19